Chapter 11

Concrete Categories

CONCRETE CATEGORIES

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1. CLASSIFICATION OF CONCRETE

Concrete, for example, can be classified according to the production method or to the type. The following table gives an overview about the main categories:

Production methods and types of concrete

Production methods	Concrete types
Ready-mixed concrete	Plain concrete
Site mixed concrete	Reinforced concrete
Shotcrete	Pre-stressed concrete
Roller compacted concrete	Lightweight concrete
Pumped concrete	High performance concrete
Slipforming	Fibre reinforced concrete
Underwater concrete	Mass concrete
Vacuum concrete	Mortars
Steam curing concrete	Repair mortar
Autoclaved concrete	Flowing fill
	Heat resistant concrete
	Concrete for aggressive environment
	Coloured concrete

2. PLAIN CONCRETE

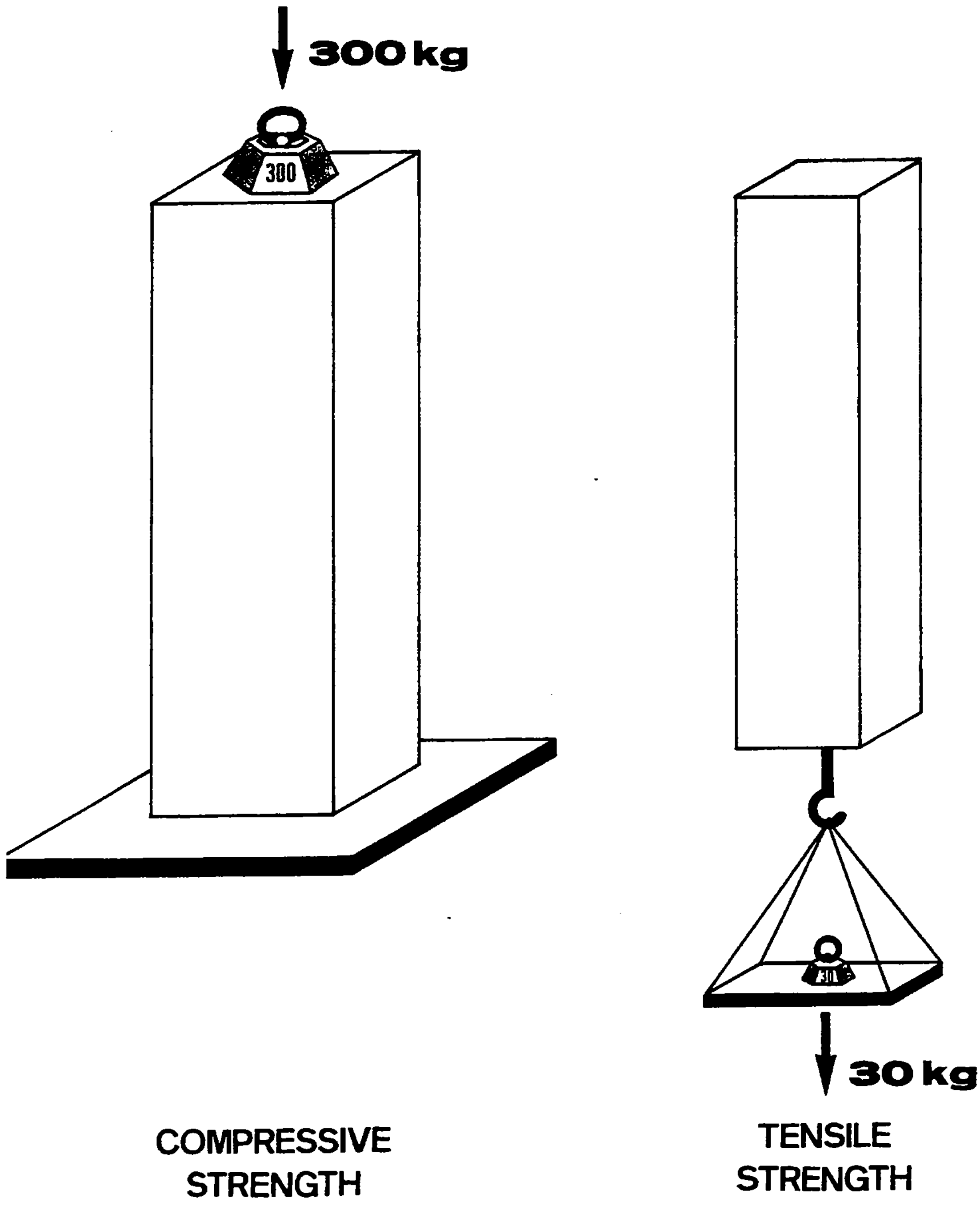
Plain concrete containing no steel reinforcing bars or wire, or containing not more than two tenth of percent of reinforcing to reduce shrinkage and temperature cracking.

3. REINFORCED CONCRETE

3.1 Introduction

Concrete is a brittle material and has therefore as all such materials a high compressive but a poor tensile strength. The compressive strength of concrete is about 10 times greater than the tensile strength. When, however, a reinforcement is used, the tensile strength is equal or greater than its compressive strength, that means, the steel is carrying the tensile stress and the concrete takes up the compressive strain; the most concrete structures are reinforced.

Fig. 1: Compressive and tensile strength of concrete



Reinforcement is the term used to describe the steel bars and small or large welded wire fabric positioned in concrete to increase its tensile stress. Many materials have been tried as reinforcement in concrete.

Steel is universal accepted and used. Reasons for practical utilisation of steel as reinforcement in concrete are as follows:

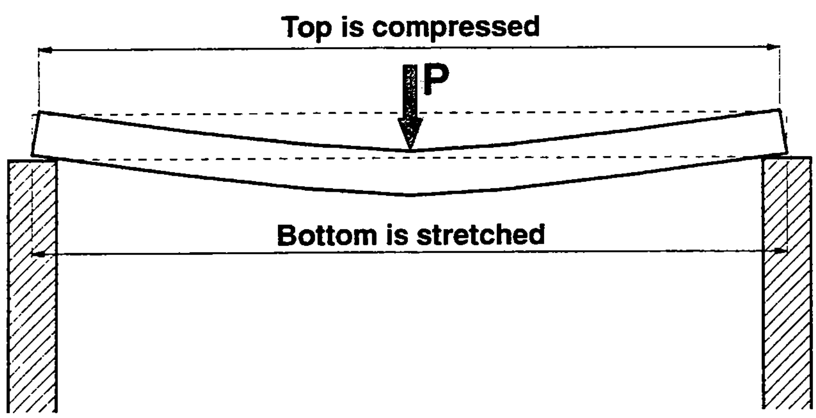
- Steel has a high tensile strength
- Very similar coefficient of thermal expansion of both materials (concrete and steel)
- Concrete protects steel against corrosion
- Satisfactory bond between both concrete and steel

3.2 How Reinforcement Works?

Concrete can be subjected to a number of tensile forces including a straight tensile pull, bending, and forces resulting from temperature and moisture changes. Concrete is often subjected to a straight tensile pull as in round structures such as water tanks and farm silos.

Pressures within the tank tend to push the two halves apart. Reinforcing steel in the wall holds the tank halves together. The steel must be around the entire tank wall since the outward pressures act in all directions. For round, structures, the reinforcing steel is usually placed near the centre of the wall cross section. In concrete beams only part of the beam contains tensile forces. Therefore, the location of the reinforcement is just as critical as the amount used to resist the bending loads; the reinforcement is placed near the lower side.

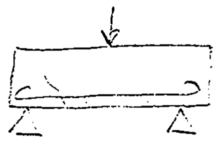
Fig. 2: Location of compressive and tensional forces in a simple beam



3.3 Placement of Reinforcement

The size, location and spacing of the reinforcement are designed in advance by engineers and are an important part of the design of the whole reinforced concrete structure. All reinforcement should be placed so that it is protected by an adequate coverage of concrete.

Concrete cover of reinforcement, as specified in the standards are between 10 to 50 mm. (for different types of structure and environmental conditions). In recent years, great strides have been made in reinforced concrete technology. Reinforcing bars are constantly being improved. The deformed bars used today bond to the concrete much more firmly than those used years ago. This improvement was achieved by changing the shape of the deformity or lugs. A recent development is high-strength steel reinforcing bars. When high-strength steel is used, the amount of reinforcing steel can be reduced.



4. PRESTRESSED CONCRETE

4.1 Overview

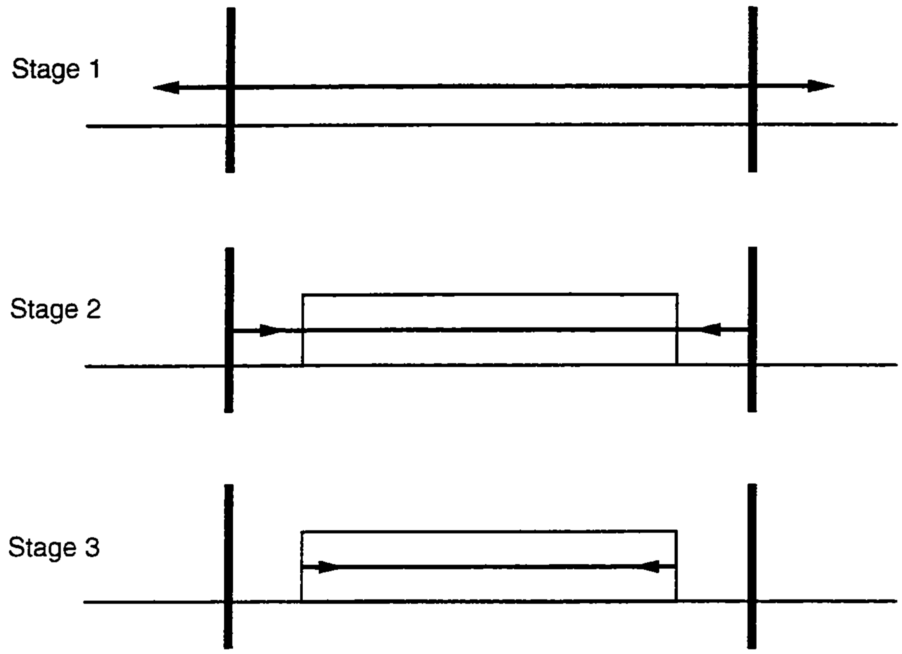
One of the disadvantage of ordinary reinforced concrete is that a reinforced concrete member develops cracks on the tension side before the reinforcement is stressed to its design load. The maximum possible elongation of concrete is about 0.01 to 0.02 %, whereas the elongation of the reinforcement when stressed to 150 MPa is about 0.06%. The crack widths are proportional to the steel stress and, in the case of plain rods, to the diameter of the reinforcing elements.

In **prestressed concrete**, large and carefully located compressive forces are introduced into high-strength concrete for increased flexural resistance or load-carrying capacity. A permanent state of induced compression is thus established and this transforms concrete into an elastic material which will carry forces that would otherwise cause critical tension or cracking.

4.2 Pre-tensioning Method

Tendons of high-tensile wire are tensioned between end grips or anchorages before the concrete is cast. The tension is usually applied by a single-strand hydraulic jack. After the concrete has hardened, the tension is released and prestress is transferred by bond from the tendons to the concrete. The method is very suitable for mass production with good factory control.

Fig. 3: Pre-tensioning of concrete



How it works:

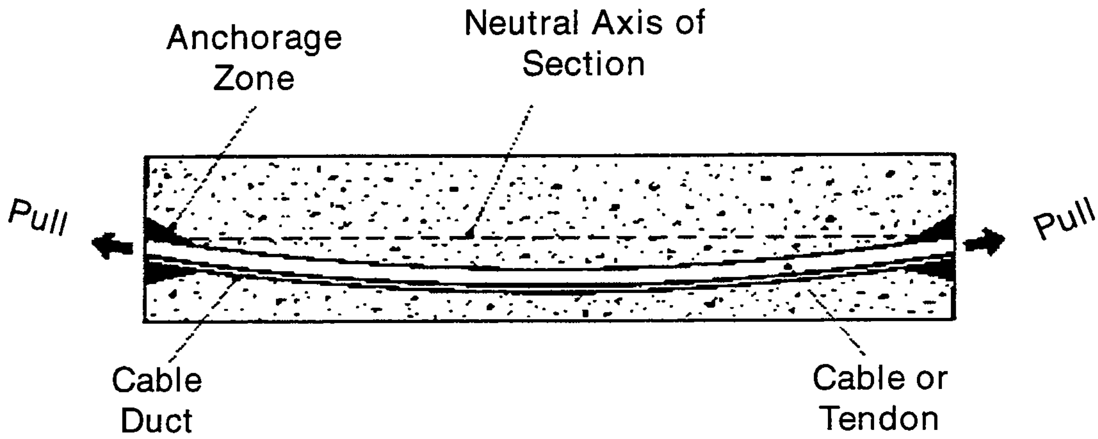
- Steel is first tensioned between fixed abutments
- Concrete is then cast in moulds around the steel
- Steel is released from the abutments as soon as the concrete achieves sufficient strength
- The force is transferred through bond of the concrete

This method is mainly suitable for factory production where larger numbers of similar or identical units are required.

4.3 Post-tensioning Method

In the post-tensioning method the concrete is usually cast with sheathed or pneumatic-core formed ducts and is allowed to harden. It is then prestressed by tendons which are located usually within the ducts or otherwise outside. When the tendons are within the ducts, the cables are fixed by pressing grout into the ducts and thus anchoring the steel to the concrete.

Fig. 4: Post-tensioning of concrete



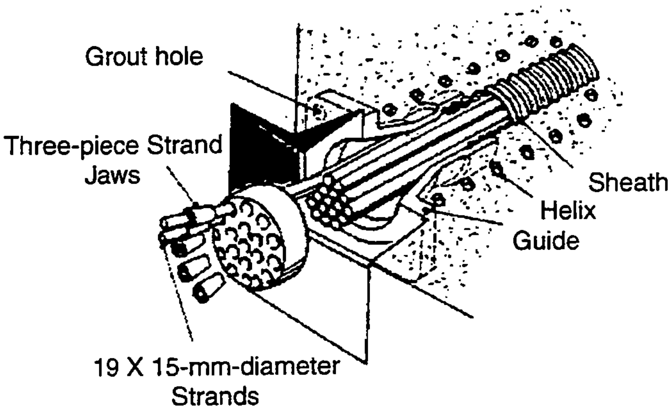
How it works:

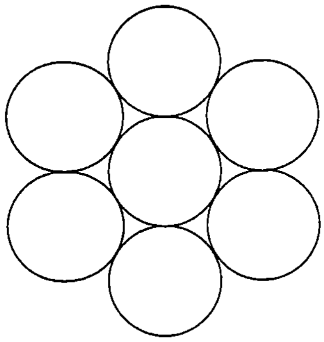
- Tendons are placed inside the structure, usually surrounded by metal sheathing to ensure free movements with relation to the structure, after the concrete has been cast.
- As soon as the concrete attains sufficient strength, tendons are stressed and their ends are anchored against the concrete to transfer the pre-stressing forces onto the structure.

Construction procedure:

- Cast beam with duct inside
- Thread pre-stressing cable
- Tension cable with hydraulic jack(s)
- Lock cable at anchorage and crop cable
- Grout cable duct
- Concrete over anchorage block

Fig. 5: Equipment: Post-tensioning





Seven-wire Strand

4.4 Application and Uses of Pre-stressed Concrete

Typical prestressed concrete products are:

- Bridge girder beams and segments
- Complete frames for precast building construction
- Dams, pipes, tanks
- Floor beams, reinforcing elements, joist and box sections
- Floor, road and aerodrome slabs
- Bearing piles
- Rail sleepers
- Telephone and electric power-transmission poles

5. PRECAST CONCRETE

5.1 Purpose of Precast Concrete

It has always been common practice to place concrete directly after mixing into its permanent, final position in the form of a structure, paving or other construction. By this classical way of concreting, the so called „cast-in-place“ or „cast-in-site“ concrete is obtained. Today, however, attempts are made to rationalise building-construction, due to shortage of man-power and rise of wages, as well as to increasing requirements on quality and uniformity of concrete. Therefore, several processes are transferred from site to stationary installations or special plants. These processes include the preparation of aggregate, the pure batching of concrete ingredients and the mixing of fresh concrete.

A further possibility of rationalising is the precast concrete - the delivery of hardened concrete construction parts to the construction site.

Formwork and reinforcement are more and more standardised and whole systems are manufactured in mass production in a factory.

Precast concrete means:

Concrete that is cast in a mould in a factory or on site or elsewhere. When sufficiently strong, the precast elements are delivered to the construction site, where they are erected in their final (service) positions.

Precast concrete is produced, if a stationary plant supplies various building-sites or if temporary production installations were placed on a large building-site. In other words, if concrete up to the hardened stage is manufactured at a place away from the final position in the building, we are dealing with a precast concrete. Precast concrete may be plain concrete or reinforced or prestressed.

5.2 Advantages of Precast Concrete

The main benefits of precast concrete are:

- Speeding the on-site processes of construction, replacement of manual masonry work by mechanical assembling;
- Continuity of processes regardless of weather and seasonal conditions;
- Better utilisation of skills, through centralisation and intensification of activities, and use of less skilled labour through training and specialisation;
- A high degree of sophistication concerning concrete composition and material utilisation and possibilities of closer control of all manufacturing activities and qualities of materials and products;
- Maximum accuracy of mould, re-use of moulds and equipment and the best use of techniques of prestressing;
- Most economical method of placing and compacting.

Of course, apart from these advantages there are also some disadvantages, e.g. difficulties arising from the transport of large elements. The individual design of buildings is limited and high investment costs of stationary installations are required.

Therefore, it has to be decided, in each case, according to the type of building and elements, and based on economical and aesthetic aspects, whether cast-in-place or precast concrete should be chosen.

The application of precast concrete has increased considerably in proportion to the entire concrete consumption over the past decades; but not as much as that of ready-mixed concrete.

5.3 Precast Concrete Products

Since many decades concrete products have been manufactured in mass production in small workshops, medium size or large factories, e.g. blocks, bricks, roofing tiles, steps, paving slabs, kerbs, piles, posts, well rings, manhole covers, sewer and drain pipes, cable and heating ducts, floor tiles, architectural cast stone and other ornamental concrete. Centrifuged reinforced or prestressed pipes are manufactured with diameters of up to 2 m.

To produce special effects on the surface of the concrete elements, special aggregates are used. Thus, Terrazzo is coloured marble or similar material embedded in cement paste and polished to a smooth finish as decor for walls and floors.

Granolithic concrete is a hard-wearing surface on floors, the aggregate being crushed granite or other hard stone.

5.4 Size and Handling of Precast Elements

A variety of types and sizes of precast structural units is manufactured for various types of buildings. Their mode of transportation and assembling varies as well. There are posts, beams, slabs of up to 30 m length, bridge-segments weighing up to 90 t walls and even three-dimensional cells.

Precast elements can be manufactured with decorative finishes or even water, sewage, heating, air-conditioning or electrical installations. Thus, all-equipped and finished rooms (bath-room units, kitchens, elevator-shafts etc.) can be supplied to the building site.

The manufacturing process is basically the same as for cast-in-place concrete: Mix design including possible additions, dosing, mixing, placing in moulds, compaction, possibly prestressing of reinforcement, curing, demoulding, possibly further curing. With stationary methods of production, all processes are carried out at the place of casting, before the products are removed. With conveyor methods, moulds and products are moved after each operation.

A special feature of precast concrete fabrication is the necessity for the placed concrete to pass quickly and without damage - to the next stage of production. The faster this can be achieved, the shorter the production cycles and the more efficient the utilisation of costly moulds and production installations.

5.5 Requirements to Precast Concrete

Note:
Precasting puts heavy demands on concrete properties

Precast elements are subjected to excessive stresses due to repeated transportation and storage. Stresses during demoulding, transport and assembling can be higher than later-on during loading at service.

Depending on the application in question, „green" strength, demoulding time, the ability to withstand transportation and stacking or prestressing can be decisive. These various criteria cannot be brought to a common denominator, but empirical correlation to compressive strength do exist. So, in practice, the problem is usually solved by specifying mandatory threshold ratings for compressive strength.

Note:
The initial strength development is of vital importance for precast concrete.

Acceleration of hardening by optimising the concrete mix is subject to limitations, but it is possible in many cases to achieve sufficient early strength by using rapid-hardening cements. With a suitable brand of cement, demoulding times can be reduced by up to 16 hours, whereas prestressing can already be applied after 48 hours.

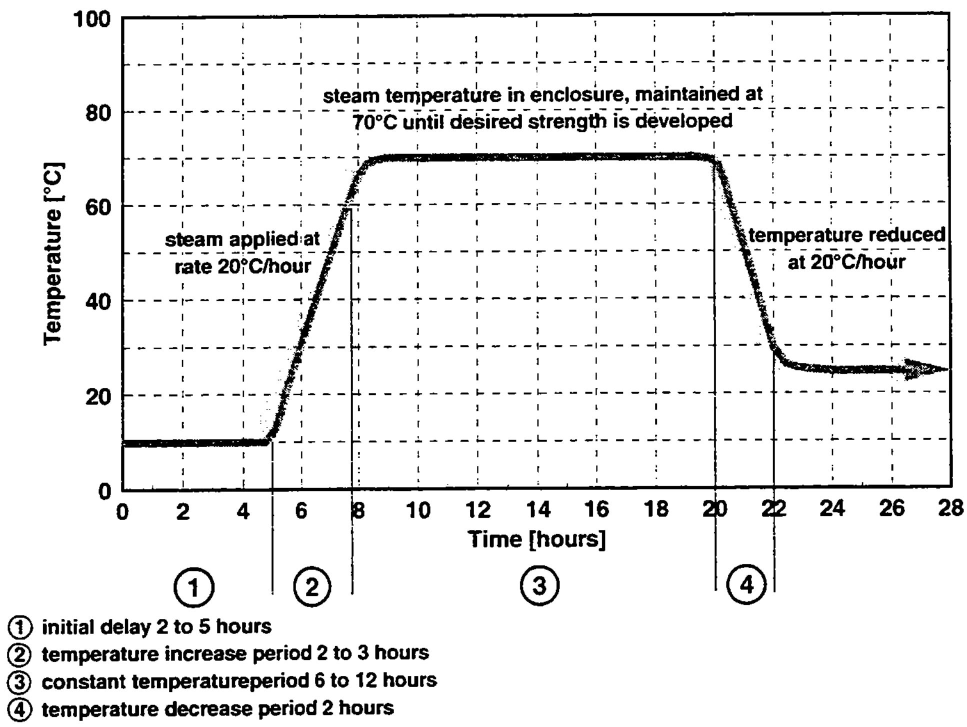
In some cases it is justified, from a technical and economical point of view, to accelerate hardening by special curing.

5.6 Curing

Various methods to accelerate hardening of precast concrete are used. However, many of these methods are cost intensive. Heat treatment in various forms is predominant. Heat can either be applied externally on the moulds, or led directly into the concrete or generated inside the concrete. The latter is accomplished by establishing an electric circuit through the fresh concrete.

External heat can be applied by vapour, hot water, oil bath or infrared radiation. Most common is the **curing in live steam** at atmospheric pressure.

Fig. 6: Time-Temperature-Diagram of a typical live steam concrete curing



The steam-curing must have an optimum cycle adapted to the element to be produced. This cycles consists of:

- An initial delay prior to steaming (at least 2 hours)
- Increasing temperature (by not more than 20 °C per hour)

- Maintaining a constant maximum temperature (60 to 80 °C)
- Decreasing temperature (by not more than 20 °C per hour)

By **high pressure steam-curing** in autoclaves at 160 to 190 °C and corresponding pressures of about 5 to 12 bars, the 28-day strength is reached within 24 hours. This hydrothermal treatment produces reactions between silica of the aggregates and lime of the cement that do not occur with normal or steam curing at atmospheric pressure. A chemical bond between cement and aggregate improves, of course, the concrete properties. Steam-curing in an autoclave is not any more expensive than steam-curing at atmospheric pressure. The investment costs, however, are significantly higher. In an autoclave, the sizes of the produced elements are limited. Therefore, the hydrothermal process is only rarely applied for products of ordinary concrete. It is, however, used for the manufacture of lime-siliceous wall blocks and gas concrete.

Generally, all Portland cements are suitable for precasting with or without heat-treatment. The relative increase of initial strength by heat is usually higher for cements producing low heat (e.g. slag cements). High alumina cements are not suited for heat treatment.

6. LIGHTWEIGHT CONCRETE

6.1 Purpose of Lightweight Concrete

Lightweight concrete instead of normal weight concrete is mostly used, if an especially good thermal insulation of walls and roof is required. Due to the shortage of energy, this insulating concrete continually gains in importance.

Lightweight concrete is also used to reduce the weight of constructions, e.g. bridges. This load bearing concrete is called structural lightweight concrete.

Both of these purposes can be attained by one and the same material - by a structural and insulating concrete. This type of application replaces the use of a combination of different materials with different properties such as:
- Load-bearing skeletons with insulating panels, and
- Thermal insulating coats on ordinary concrete or
- Sandwich panels.

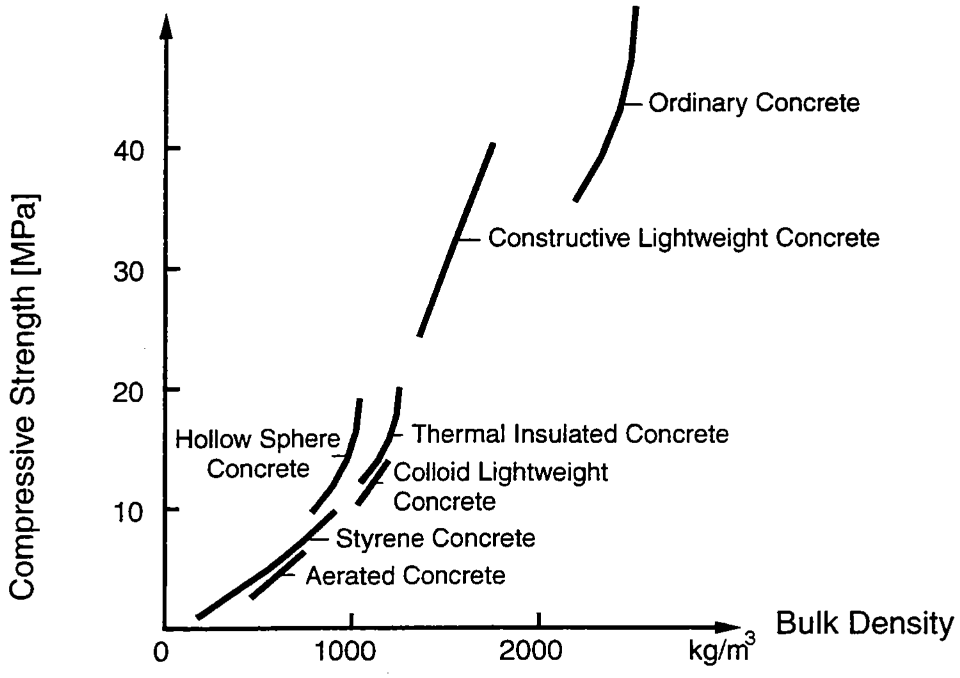
According to its purpose, different bulk weights of the concrete are chosen:

Table: Bulk density of lightweight concrete

Concrete application	Bulk density, kg/m^3
Insulating concrete	300 - 800
Structural concrete	1400 - 1900
Combined application	800 - 1400

For the latter two purposes reinforced or even prestressed concrete can be used. By decreasing the bulk weight, the thermal insulating capacity increases, strength, however, diminishes.

Fig. 7: Relation of strength and bulk density of different concrete types



Physical properties lightweight aggregate

Aggregate type	Particle shape, surface texture	Density [kg/m³]	Bulk density [kg/m³]	24 h-water absorp. [wt-%]	Concrete Compr. strength [MPa]	Concrete Unit weight [kg/m³]
Aggregates for high strength lightweight concrete, > 15 MPa						
Expanded clay	Rounded and slight rounded part.	Coarse: 600 to 1600 Fine: 1300 to 1800	300 to 600	5 to 30	10 to 60	1000 to 1700
Exp. shale and slate	Angular slightly rounded, smooth surface	Coarse: 800 to 1400 Fine: 1600 to 1900	400 to 1200	5 to 15	20 to 50	1300 to 1600
Fly ash	Similar to exp. clay	1300 to 2100	600 to 1100	20	30 to 60	15000 to 1600
Foamed blast furnace slag	rough and open pored	1000 to 2200	400 to 1100	10 to 15	10 to 45	1800 to 2000
Sintered colliery waste	Angular open pored	1000 to 1900	500 to 1000	15	10 to 40	1400 to 1600
Aggregates for medium strength lightweight concrete, 3.5 - 15 MPa						
Pumice	Rounded, rather smooth surface	550 to 1650	350 to 650	50	5 to 15	1200 to 1600

Aggregates for high strength lightweight concrete, 0.5 - 3.5 MPa						
Perlite	Rounded shape, rough surface	100 to 400	40 to 200	---	1.2 to 3.0	400 to 500
Vermiculite	Cubical	100 to 400	60 to 200	---	1.2 to 3.0	300 to 700

6.2 Types of Lightweight Concrete

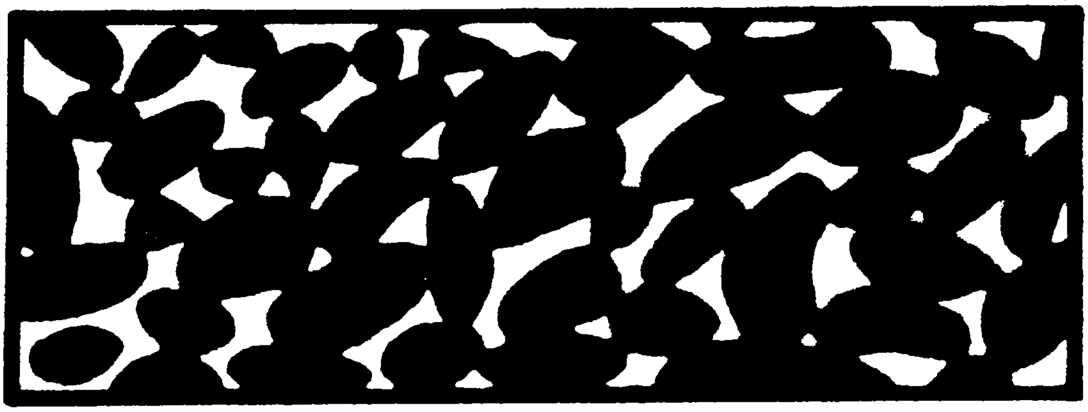
The best and least expensive thermal insulation is achieved with occluded air which does not contribute to heat convection; just like animal fur and human hair, where not the hair itself is the insulating medium but the air trapped in between. All types of lightweight concrete contain air voids, but the manner of incorporation varies.

6.2.1 „No Fines Lightweight Concrete"

The simplest way to obtain a lightweight concrete is one that would be the greatest mistake for ordinary concrete:

Only coarse aggregates, i.e. only one particle size fraction with 35 - 50 % voids, is used. Just enough cement paste to bind the grains of the aggregates but not to completely fill the voids, is added.

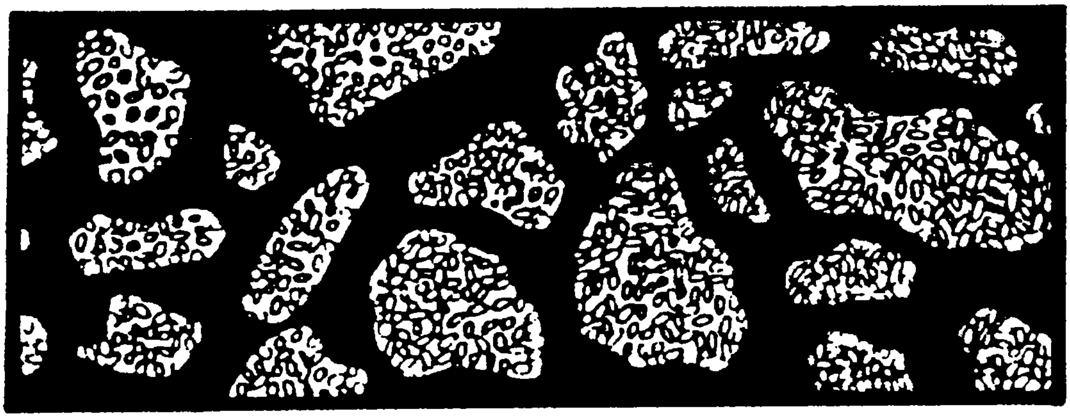
Fig. 8: View of 'no fineness aggregate' lightweight concrete (water draining concrete)



6.2.2 Concrete with Lightweight Aggregates

The voids are inside the aggregates

Fig. 9: View of lightweight concrete with lightweight aggregates



6.2.3 Cellular (aerated) Concrete

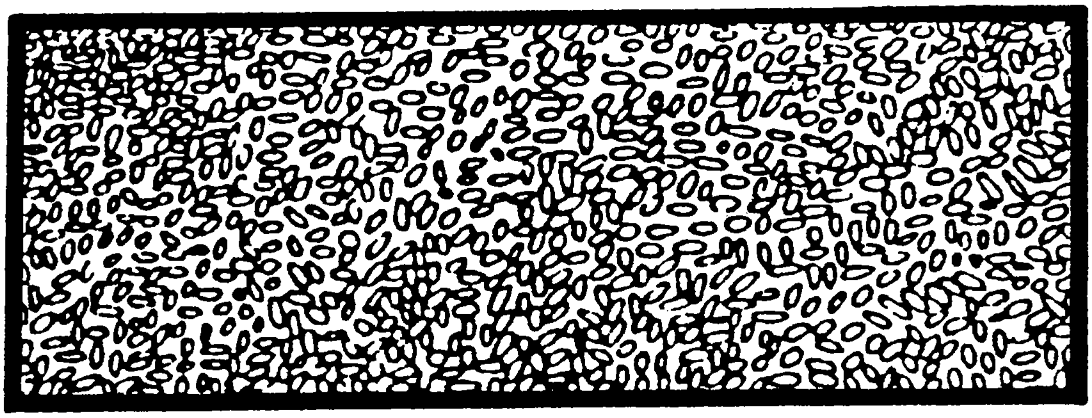
- The pores are within the cement paste or mortar.
- They are produced during mixing by foaming agents. The product is called aerated or foamed concrete.
- Another method is the generation of gas after casting by a chemical reaction within the unhardened mix. This type of concrete is called gas concrete.

„No fines concrete" can also be produced with lightweight aggregate. On the other hand, lightweight aggregate can be combined with aerated mortar. In both cases, lower bulk weights are obtained than in the ordinary lightweight aggregate concrete (800 to 1600 kg/m^3 with compressive strengths from 1.5 to 15 MPa).

When lightweight concrete is used, the differences in moisture content, desiccation and shrinkage in relation to ordinary concrete must be considered. According to the pore structure, the absorption capacity and frost resistance of the lightweight concrete may be higher or lower than those of ordinary concrete. In lightweight concrete the steel reinforcement is less protected against corrosion and therefore very often has to be covered by a protective coating.

Poudre aluminium qui réagit avec OH^- => H_2

Fig. 10: View of cellular concrete



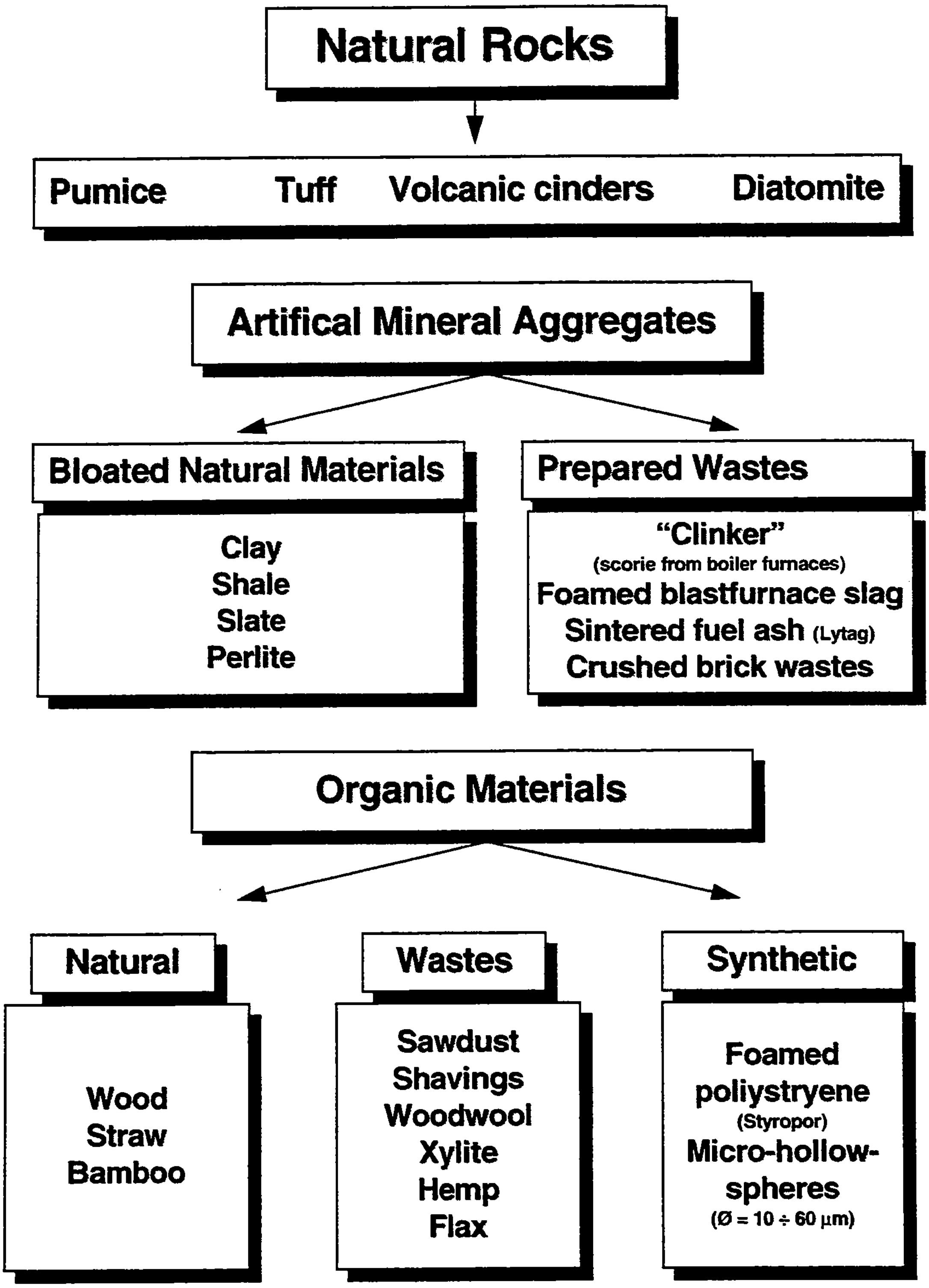
6.3 Concrete with Lightweight Aggregates

Porous aggregates are sometimes found as natural rocks, mostly of volcanic origin; they can also be produced artificially from natural raw materials, industrial by-products or wastes. Even organic substances in the form of natural products, waste-products, refined or synthesised fillers are used in lightweight concrete.

Artificial lightweight aggregates have different trade names, even for similar products.

These aggregates are usually crushed and screened as well .The bulk weight of finer particle size fractions generally is higher than that of coarser fractions. Often, coarse lightweight aggregate is used together with normal sand.

Fig. 11: Lightweight aggregates



Concrete manufacture with lightweight aggregate is principally subject to the same rules as ordinary aggregates; however, for mix designs, placing and compaction some particularities must be observed. Especially the absorption of mixing water by porous aggregates and the fast stiffening of concrete must be taken into account when dosing water. Therefore, it is recommended to saturate the aggregates with water before dosage. Very light aggregates tend to float on top of the concrete mix, resulting in segregation. This can be prevented by the addition of admixtures.

Due to these particularities in mixing and placing, lightweight aggregates are preferably used in precast concrete rather than in cast-in-place. It is applied in the manufacture of bricks, wall panels, floor and roof slabs.

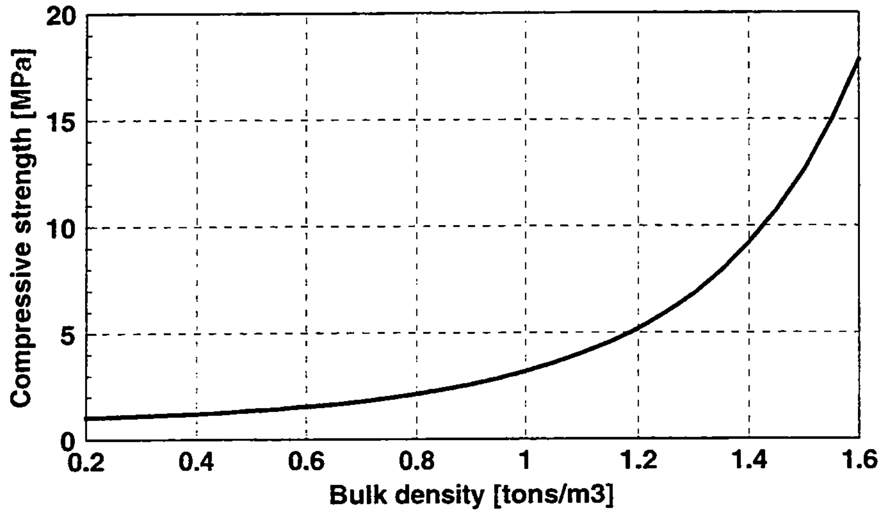
It should be mentioned that sometimes natural products, such a straw, hemp, flax, bamboo, wood shavings and sawdust are used in lightweight concrete manufacture. Insulating panels and blocks (Durisol) are industrially manufactured with wood-wool, sawdust and shavings together with cement.

In extremely light concretes small spheres of expanded Polystyrene („Styropor") replace the mineral lightweight aggregates. The bulk weight of Styropor can be as low as 15 kg/m^3.

6.4 Aerated (foamed) Concrete

The simplest way to obtain a high pore content is to use concrete mixes with a high water content. Through quick hardening by vapour and desiccation, voids are created. A higher pore volume (up to 30%) is attained by foaming agents (hydrolysed proteins or resin soaps). Either a separately produced foam is injected into the concrete mix by pressure, or the foam is produced in the quick rotating concrete mixer by the direct addition of a foaming agent. The concrete mix must contain only fine aggregates; generally, a cement mortar with sand up to 3 mm. This procedure can easily be carried out on site and is used e.g. for roof insulation. It is, however, not widely applied as it is very difficult to regulate the pore content and the mechanical properties. The relations between bulk weight and compressive strength is recorded in the following figure:

Fig. 12: Relation of strength to density to foamed concrete



Aerated concrete (up to 30 vol.-% pore content) has to be distinguished from air-entraining concrete which, due to its 3 to 5 vol.-% pore content, is used for structural purposes demanding high frost/thaw resistance.

6.5 Gas Concrete

The voids are developed within the unhardened mix, usually by hydrogen generated by the action of lime on fine Aluminium powder used as an admixture (0.2% of cement weight). Only occasionally used is oxygen from peroxides or acetylene from carbide.

Cement and sand (type „Siporex") or quick lime with various siliceous components (type „Ytong" with ground shale or fly ash) are applied as basic materials. In some procedures a combination of cement and lime in various proportions is used („Durox", „Calsilox", „Hebel"). In order for the mass to be bloated by gas, the components must be very fine (to compare with the rising of bread). Therefore, in gas concrete a mortar is used and not a concrete mix with coarse aggregates. It is important that the generating of gas is synchronised with the stiffening of the mass, so that the gas cannot escape and the cake expands without collapsing when gas generation has stopped. Before hardening, the demoulded blocks are cut with wires into blocks or slabs of desired sizes.

Curing generally (always when lime is applied) takes place in autoclaves. By a chemical bond during the hydrothermal process, the aggregates are incorporated into the binding material. This fact, together with the regular pore structure create a good relation between strength and bulk density, for example:

Note:
At bulk densities of 800 kg/m^3 equal compressive strengths as for lightweight concretes with bulk densities of more than 1200 kg/m^3 are reached.

With gas concrete mainly wall blocks, reinforced roof slabs and wall panels, even with a precast surface coating, are produced.

7. HIGH PERFORMANCE CONCRETE (HPC)

This is a term usually used to describe concretes made with carefully selected high quality ingredients, optimised mixture designs, and which are batched, mixed, placed, compacted and cured to the highest industry standards. Typically such concretes will have a low water/cementing materials ratio of 0.40 or less, and generally much less. Most HPCs have water/cementing materials ratios in the range of 0.25 to 0.35 with 0.30 generally die optimum value. The achievement of such low water/cementing materials ratios depends on the use of large quantities of superplasticizers, the use of which leads to high workability, another common characteristic of mixes.

Because of the formulations used, HPC almost always has a higher strength than normal concrete. However, strength is not always the prime required property, and HPC is valuable where any of the following properties are required:

- High strength
- Very-high strength
- High early strength
- Abrasion resistance
- Low permeability
- Low gas and water absorption
- Low diffusion coefficient
- High resistivity
- Resistance to chemical attack
- High modulus of elasticity
- High resistance to freezing and thawing damage
- Volume stability
- Inhibition of bacterial or mould growth

In 1993 the ACI Committee on High-Performance Concrete proposed the following Definition of High Performance Concrete:

High Performance Concrete:

Concrete meeting special performance requirements which cannot always be achieved routinely using only conventional constituents and normal mixing, placing and curing practices.

These requirements may involve enhancements of the following:

- Ease of placement and compaction without segregation
- Long-term mechanical properties
- Early-age strength
- Toughness
- Volume stability
- Service life in severe environments

7.1 High Strength Concrete

The definition of high strength changes from time to time. According, to the American Concrete Institute, high strength is defined as that over 41 MPa compressive strength. This value was adopted by ACI in 1984 but is not yet hard and fast, because ACI recognises that the definition of high-strength varies on a geographical basis. Prof. J. Francis Young of the University of Illinois at Champaign-Urbana has developed a strength classification system that, though not yet adopted by a recognised authority, is a helpful tool for describing high-strength concretes (see following table).

Strength classification of concrete

Parameter	Conventional concrete	High-strength concrete	Very high strength concrete	Ultra high-strength concrete
Strength, MPa	<50	50 - 100	100 - 150	>150
Water/cement ratio	>0.45	0.30 - 0.45	0.25 - 0.35	<0.25
Chemical admixtures	not necessary	WRA/RWR *)	HRWR **)	HRWR **)
Mineral admixtures	not necessary	Fly ash	Silica fume	Silica fume
Permeab. coeff. (water), cm/s	$>10^{-10}$	10^{-11}	10^{-12}	$<10^{-13}$
Freeze-thaw protection	needs air entrainment	needs air entrainment	needs air entrainment	no freezable water

*) **WRA = Water Reducing Admixture;** **) **HRWR = High Range Water Reducer**

Compositions of typical HPC mixtures can be seen in the following table:

Typical HPC mixtures

Component	Mix 1	Mix 2	Mix 3
Water, kg/m³	195	135	130
Cement, kg/m³	505	500	513
Fly ash, kg/m³	60	---	---
Silica fume, kg/m³	---	30	43
Coarse aggregate, kg/m³	1030	1100	1080
Fine aggregate, kg/m³	630	700	685
Water reducer, ml/m³	975	---	---
Retarding agent, L/m³	---	1.8	--
Superplasticizer, L/m³		14	15.7
w/c ratio	0.35	0.27	0.25
Strength at 28 d, MPa	65	93	119
Strength at 91 d, MPa	79	107	145

8. SHOTCRETE

8.1 INTRODUCTION

Shotcrete is the name given to mortar or concrete conveyed through a hose and pneumatically projected at high velocity onto a backup surface. The force of the jet impacting on the surface compacts the material so that it can support itself without sagging or sloughing, even on a vertical face or overhead. Other names are also used for some types of shotcrete, e.g. *gunite,* but only *sprayed concrete* is sufficiently general and is indeed the preferred term in the European Union terminology.

The properties of shotcrete are no different from the properties of conventionally placed mortar or concrete of similar proportions: it is the method of placing that bestows on shotcrete significant advantages in many applications. At the same time, considerable skill and experience are required in the application of shotcrete so that its quality depends to a large extent on the performance of the operators involved, especially in control of the actual placing by the nozzle.

Because shotcrete is pneumatically projected on a backup surface and then gradually built up, only one side of formwork or a substrate is needed. This represents economy, especially when account is taken of the absence of form ties, etc. On the other hand, the cement content of shotcrete is high. Also, the necessary equipment and mode of placing are more expensive than in the case of conventional concrete. For these reasons, shotcrete is used primarily in certain types of construction: thin, lightly reinforced sections, such as roofs, especially shell or folded plate, tunnel linings, and prestressed tanks. Shotcrete is also used in repair of deteriorated concrete, in stabilising rock slopes, in encasing steel for fireproofing, and as a thin overlay on concrete, masonry or steel. If shotcrete is applied to a surface covered by running water, an accelerator producing flash set, such as washing soda, is used. This adversely affects strength but makes repair work possible. Generally, shotcrete is applied in a thickness up to 100 mm.

There are two basic processes by which shotcrete is applied. In the *dry mix process* (which is the more common of the two, in many parts of the world) cement and damp aggregate are intimately mixed and fed into a mechanical feeder or gun. The mixture is then transferred by a feed wheel or distributor (at a known rate) into a stream of compressed air in a hose, and carried up to the delivery nozzle. The nozzle is fitted inside with a perforated manifold through which water is introduced under pressure and intimately mixed with the other ingredients. The mixture is then projected at high velocity onto the surface to be shotcreted.

8.2 DRY MIX AND WET MIX SYSTEMS

8.2.1 Dry Mix

Two distinct methods of spraying concrete exist, namely the dry mix and wet mix systems. In the dry mix system, a mixture of cement, sand and large aggregate, if used, but with no added water, is fed into a special mechanical feeder - the gun - and metered into a high pressure delivery hose. The material is then carried on a stream of compressed air through the hose to a special nozzle which is equipped with a water injection system operated by a valve which is under the direct control of the nozzleman. The function of the nozzle is to convert the incoming stream of dry mixed material into concrete of the correct consistency and project it at a specified point, some distance away, where it will impact on a surface and stick there.

The original dry mix concrete spraying system has been developed over the years to a high degree of efficiency but several other types of gun are now in use. Their mechanisms are different but the basic principle is the same. This is to feed dry mix into a chamber where high pressure air blasts it down a hose.

8.2.2 Wet Mix

In the wet mix concrete spraying system all the materials, including water, are thoroughly mixed before being introduced into a pump. This can be a simple, non-mechanical device such as a CEM pump or any one of a number of mechanical pumps, usually of the smaller variety, currently available. By such means the concrete is pumped or squeezed along the delivery hoses. It is, of course, travelling at a relatively low velocity but the nozzle converts the pumped concrete into shotcrete by the introduction of compressed air - not water as in the dry mix system - which blows the concrete at high velocity onto the surface to be coated.

8.2.3 System Advantages

Each system possesses certain advantages. The wet mix system would appear to diminish the reliance on operator technique at the nozzle as the water is added at the mixer as in ordinary concreting practice. However, very strict control is required to ensure that the mix possesses the required characteristics pumpable but not too pumpable! Certainly the wet mix system produces less dust and rebound and therefore finds favour in tunnels where its high output and ability to produce a more recognisable large aggregate concrete are of advantage. But it would appear that the lead that has been built up by the dry mix system will ensure that its popularity is maintained.

8.3 Shotcrete and Rebound

Rebound consists mainly of sand and aggregate - with a small cement content - which does not adhere to the surface of application, the reinforcement or the fresh concrete layer itself, but which bounces back out of the placing area or otherwise becomes detached from the surface. Rebound percentages can be anything from 5% to 50% depending on various factors. It is expensive and wasteful and rather unpleasant for the nozzleman. Moreover, there is always the danger that instead of falling clear the rebound may become lodged particularly in the corners of the work and behind the reinforcement. Should rebound remain trapped in the finished work this results in zones of weakness.

8.4 Strength and other Properties

Properly applied shotcrete is a versatile structural material, possessing great durability, and is capable of excellent bond with concrete, masonry, steel and other materials. A mix designed for placing by traditional methods can show up to 30% increase in strength if applied as gunite and one rarely hears of any shotcrete strengths below 30 MPa while strengths in excess of 70 MPa have frequently been obtained. Such strengths are obtained partly by virtue of the low water/cement ratio which falls within the range 0.35 to 0.40 by weight, which is lower than most values for conventional concrete mixes and partly by the packing action as each particle is impacted into the material already in place.

This same action, in part, explains the high bond strength of shotcrete to other material faces which should be presented in a clean, roughened and damp state. If, for example, concrete was sprayed onto such a face, it should be impossible to pull the hardened shotcrete away without pulling the face of the original concrete away with it. The compressive strength and bond strength of shotcrete are two of its more important characteristics.

Other properties include flexural-tensile strength at 4 to 5 MPa drying shrinkage in the range 0.05 to 0.10% density generally 2240 kg/m^3 to 2320 kg/m^3 and superior resistance to acid attack and abrasion. Shotcrete has performed well in permeability tests and one test at least has indicated that a 50 mm thick gunite specimen would show no water percolation at all up to 700 kN/m^2. A very valuable property of shotcrete from the practical point of view is its ability to support itself in thickness of up to 50 mm at a time in the overhead position and, of course, to a much greater thickness on a vertical surface without the use of a face shutter. Thus, thickness can be reduced with consequent savings and alternative methods of approaching certain types of work considered.

8.5 Uses of Shotcrete

Ever since its introduction, shotcrete has been used for repair works. Structural repairs are often needed following fire damage, impact or abrasion including erosion of marine structures, or due to poor concrete in the original construction, incorrect positioning of reinforcement causing lack of cover, design faults, chloride attack or simply old age.

Cosmetic or superficial repairs are sometimes required because of poor finishing of the original construction, honeycombing of the concrete, incorrect alignment due, for instance, to shutter slips, or wear and tear, while refractory repairs often form part of maintenance programmes in industrial installations to the linings of furnaces, reactors or chimney stacks which are subject to chemical attack and very high temperatures.

A shotcrete repair carried out correctly will produce a high strength material with a complete bond to the original structure provided by a compact and portable plant which can be operated at a convenient point some way away from the area to be repaired.

It should be stressed that the preparation of the works is of paramount importance. Failure can normally be traced back to insufficient cutting out of unsound concrete or insufficient cleaning of existing steelworks both of which will lead to a failure of the bond between the shotcrete and the parent surface or reinforcement.

Many brick and masonry arch structures such as bridges and viaducts were constructed 100 years ago or even more. It is a tribute to their designers and builders that they have lasted so long but time does leave its mark and the loading imposed upon them today are often far in excess of their design loadings. Such structures can be strengthened by spraying a new concrete arch underneath the original arch with minimal access requirements and no shuttering.

In original construction, perhaps the best known use of shotcrete is in the building of swimming pool shells where the flexibility of the medium is reflected in freedom of design. The techniques developed for building pools have more recently been adapted for the construction of skateboard parks with some success.

Some excellent examples of imaginatively designed thin section shell roofs also exist and pre-shot gunite elements have been produced ranging from thin sewer-lining segments to large curved capping pieces for North Sea Oil structures.

The construction of houses and even small schools is now being developed using reinforced shotcrete each side of a lightweight insulating layer.

As a protective coating, shotcrete has many uses. When an excavation is opened up, weathering of the newly exposed face quickly takes place. On an embankment surface deterioration can be a long term problem while in a steep sided cutting the falling of even small pieces of rock can cause serious danger to those working below. A relatively thin coating of lightly reinforced shotcrete can seal the surface and protect it particularly if the treatment is carried out at an early stage. Many steel pipelines, particularly for North Sea gas and oil are coated with shotcrete for protection and negative buoyancy where they cross rivers on their journey across the country. The portable nature of the plant makes it ideal to carry out such work on the riverbank and circular encasements are completed without shuttering.

It is said that if we have space for a man and a hose, we can place concrete no matter what the problems of access. Small amounts of concrete are often needed to fill pockets, for example, after completion of surrounding structures and this can be done without recourse to buckets and ropes and without the need for shutters or letterboxes. With the dry mix system, concrete can be blown through hoses in excess of 100 metres horizontally or vertically.

8.6 Summary: Shotcrete

The production of shotcrete relies to a great extent on the skill of the operators and there is a greater inherent variability than with in-situ concrete. The design should allow for this.

As far as quality control is concerned, the short answer is to find a good contractor and a good specification and make sure that the contractor keeps to the specification.

The process has been with us a long time. The machinery and techniques have evolved, the product exhibits certain very interesting and useful characteristics and, with proper use and control can be made to serve the contractor, the engineer, the client and ultimately the industry of which we are all a part.

9. ROLLER COMPACTED CONCRETE (RCC)

9.1 INTRODUCTION

Roller Compacted Concrete (RCC), rather than a new material is a new technique for building in concrete, which has proved very suitable for dam and road construction. Its relevant to the cement industry must be made clear from the beginning: It opens up excellent prospects to compete advantageously with traditional non-cementitious 'foes': earth and rockfill dams and asphalt pavements.

By the end of the '60s it was ascertained in the USA that less than 10% of the newly built dams were concrete dams. The implication for their future was clear: Either they were constructed more rapidly and economically or they ran the risk of becoming a species under threat of extinction. This challenge generated a more systematic search for a solution, the result of which is RCC.

9.2 WHAT IS RCC AND WHAT ARE ITS ADVANTAGES ?

Basically, the technique of building dams with RCC consists of placing concrete - of dry consistency - in layers 0.30 to1.00 m thick, which are subsequently compacted by several passes of heavy vibrating rollers. This process can be carried out without interruption along the entire length of the dam and, thus, the traditional system of erecting dams in blocks, separated by joints, is substituted by one in which the elevation of the structure is achieved uniformly. This results in a simpler RCC construction layout, with associated reductions in materials and labour costs. Even more important is that the rate at which concrete is placed and compacted is much higher than for conventional concrete dams, coming close to those achieved for earth-fill dams. As an example, in Upper Stillwater Dam (USA), RCC production peaks of 8400 m^3/day were attained. Building dams in RCC brings about huge savings to the civil engineering construction, the cost of which may become only one third of that necessary in the case of the traditional concrete dams techniques. Even more important, a project in RCC may result more economical that the alternative earth-fill dam.

9.3 DIFFERENT RCC CONCEPTS

As a consequence of its evolution, three different concepts of RCC have emerged:

- **Lean RCC**, developed by the US Army Corps of Engineers
- **Moderate in Paste RCC** or 'Rolled concrete dam (RCD)' according to Japanese practice and designation
- **Rich in Paste RCC** developed in the UK and adopted by the US Bureau of Reclamation

9.4 SUITABLE MATERIALS FOR RCC

9.4.1 Binders

Binders used in the construction of RCC dams are mainly based on Portland cement, be it pure or blended with additions. When pure Portland cement is used as the only binder, it is preferred to use cements of low or moderate heat of hydration (ASTM Types IV and II).

There is a preference for blended binders containing fly ash due to its beneficial effect on workability, the fly ash content being high, generally over 40% of the total The preferred addition for RCC is the low CaO fly ash (ASTM Type F); it can be mentioned that, for this application, fly ash of substandard quality can be used. To a smaller degree, blast furnace slag and natural pozzolans have also been used.

In different projects the fly ash has been incorporated into the mix in various ways: as part of the cement, as a separate concrete ingredient or a combination of both (this solution has been used in Santa Eugenia Dam in Spain).

A very important property of a binder to be used in RCC dam construction is extremely low heat of hydration. For instance, for a dam project in Colombia, a binder having a heat of hydration 40 cal/g at 7 days was specified, a limit which is considerably stricter than the 60 cal/g specified as a maximum for ASTM Type IV, Low Heat cement. This explains the convenience of adding large amounts of fly ash into the binder to keep the heat generation low.

9.4.2 Aggregates

Aggregates that fulfil the typical quality requirements for conventional concrete will be adequate for RCC. Of course the deleterious effects of the Alkali-Aggregate reaction should be avoided, its likelihood being low when moderate to high pozzolanic materials are included in the binder.

A special requirement is that the strength of the coarse aggregate must be sufficient to withstand the heavy compaction pressures exerted on the material by the rollers.

Regarding the grading the following applies:

- The preferred maximum size seems to be around 80 mm, although larger aggregates (up to 150 mm) and smaller (about 40 mm) have also been used.
- The grading curve for RCC differs from that of conventional concretes, particularly in the fine fraction. In particular, for **Lean RCC** a high proportion of material below 0.075 mm (between 4 and 10%) is recommended.

Some experts claim that the uniformity of the grading is not as vital for RCC as it is for conventional concrete and that the aggregates could be stored directly as a single fraction or eventually as only two fractions (see cases of Monkville and Saco de Olinda dams in the following table). That table shows that, in general, the aggregates should be stored in between 3 to 5 different fractions depending on the maximum size.

Some examples of aggregates for RCC for dams

Dam (country)	Max. size, mm	No. of fract.	Fraction size, mm
Ohkawa (Japan)	80	4	0-5, 5-20, 20-40, 40-80
Shin-Nakano (Japan)	50	4	0-5, 5-20, 20-40, 40-80
Shin-Nakano (Japan)	150	5	0-5, 5-20, 20-40, 40-80, 80-150
Castilblanco (Spain)	50	4	0-5, 5-12.5, 12.5-25, 25-50
Morales (Spain)	80	4	0-5, 5-20, 20-40, 40-80
Morales (Spain)	40	3	0-5, 5-20, 20-40
Erizana (Spain	100	4	10-6, 6-20, 20-50, 50-100
Monkville (USA	76	2	0-25, 25-76
VVillow Creek (USA)	76	3	0-20, 20-38, 38-76
Upper-Stillwater (USA)	38	3	0-4.8, 4.8-19, 19-38
Saco de Nova Olinda (Brazil)	76	2	0-30, 30-70

9.4.3 Water

The specifications for the quality of mixing and curing water for RCC are the same as for conventional concrete. Regarding quantity, the water content of RCC mixes ranges normally between 90 and 120 kg/m^3; sometimes these low values create problems if the aggregates are wet, since they may carry more water than is strictly necessary to prepare the mix (e.g. Pangue Project, Chile).

9.4.4 Chemical Admixtures

Due to the very dry consistency and high amount of fineness, the use of chemical admixtures has proved problematic for Lean RCC mixes.

For the other two types of RCC the chances of successful use of chemical admixtures are higher. For instance, air-entraining and water-reducing agents are introduced into all Japanese RCC mixtures. A water-reducing and retarding agent, at a relatively high dosage (0.9 to 1.3%), was used for Elk Creek Dam with good results.

10. FIBRE REINFORCED CONCRETE

In recent years, numerous attempts have been made to reinforce concrete by incorporating randomly distributed fibres, when fibre-reinforced plastic materials have already widely been used. For such reinforcements four groups of fibres may be considered: steel, plastic, glass and (in former times) asbestos fibres. Other special fibres, such as carbon, are far too expensive for concrete.

For reinforcing materials the important factor is the Young's modulus (= initial tangent modulus) of the fibres. If it is smaller than that of concrete, the fibre does not help to increase the tensile strength of the concrete. The various materials referred to possess the following values of Young's modulus:

Table: Young's modulus of fibres

Fibre type	Young's modulus [GPa]
Concrete	30
Polypropylene fibres	≤5
PVA fibres	30
Glass fibres	70
Steel fibres	210
Asbestos fibres	150

10.1 Different Types of Fibres

The most commonly used man-made fibres have been *steel and polypropylene,* principally in concrete, and glass, principally in cement mortar for thin section applications. Properties of some of the commonly used fibres are given in the following table:

Physical properties of various types of fibres and matrices

Material	Spec. gravity, g/cm^3	Young's modulus, GPa	Tensile strength, MPa	Elong. at breaking point, %
Acrylic	1.10	2.1	210 - 420	25 - 45
Asbestos (Chrysotile)	2.55	150	200 - 1800	2 - 3
Carbon, high modulus	1.9	380	1800	0.5
Carbon, high strength	1.9	230	2600	1.0
Cellulose	1.5	10 - 40	500	---
Cotton	1.5	5	420 - 700	3 - 10
Glass (Cem-FIL filament)	2.7	80	1050 - 3870	1.5 - 3.5
Nylon	1.1	4.2	780 - 850	16 - 20
Polyester	1.4	8.5	750 - 880	11 - 13
Polyethylene, high modulus	0.96	15 - 40	300 - 700	3 - 10
Polypropylene	0.91	3 - 15	560 - 780	8
Rayon	1.50	7.3	420 - 630	10 - 25
Steel	7.86	200	280 - 420	3.5
OPC paste	2.0 - 2.2	10 - 20	2 - 6	0.01 - 0.05
OPC concrete	2.30	20 - 35	1 - 4	0.005 - 0.015

10.1.1 Steel-fibre Reinforced Concrete

A number of steel-fibre types are available as reinforcement. Round steel fibres, the commonly used type, are produced by cutting round wires into short lengths. The typical diameters lie in the range of 0.25 to 0.75 mm. Steel fibres having a rectangular cross-section are produced by slitting the sheets about 0.25 mm thick. For improving the mechanical bond between the fibre and matrix, indented, crimped, machined and hook-ended fibres are normally produced. The aspect ratio (= length/diameter) of fibres which have been employed vary from about 30 to 250.

Fibres made from mild steel drawn wire with a diameter from 0.3 to 0.5 mm have been practically used. Round steel fibres are produced by cutting or chopping the wire; flat sheet fibre having a typical cross-section ranging from 0.15 to 0.40 mm in thickness and 0.25 to 0.90 mm in width are produced by slitting (shearing) flat sheets. Deformed fibres which are loosely bonded with water soluble glue in the form of a bundle are also available. Since individual fibres tend to cluster together, their uniform distribution in the matrix is often difficult. This may be avoided by adding fibre bundles which separate during the mixing process.

10.1.2 Polypropylene Fibre-reinforced (PFR) Cement-mortar and Concrete

Polypropylene is one of the cheapest and abundantly available polymers. Polypropylene-fibres are resistant to most chemicals and it would be the cementitious matrix which would deteriorate first under aggressive chemical attack. Its melting point is high (about 165 °C), so that a working temperature as high as 100 °C may be sustained for short periods without detriment to the fibre properties.

Polypropylene short fibres in small volume fractions between 0.5 to 1.0% have been commercially used in concrete to achieve considerable improvement in impact strength of the hardened concrete. The have low modulus of elasticity. Polypropylene fibres are available in two forms: monofilaments produced from spinnerets, and film fibres produced by extrusions. The film fibres are commonly used and are obtained from fibrillated film twisted into twine and chopped, usually into 25 - 50 mm lengths for use in concrete. The fibrillated film may also be opened to produce continuous networks for use in thin sheet manufacture. Fibrillated film may also be woven to produce flat meshes which may be used as thin cement sheet reinforcement.

Polypropylene fibres being hydrophobic can be easily mixed as they do not need lengthy contact during mixing and only need to be evenly dispersed in the mix. These are therefore added shortly before the end of mixing the normal constituents. Prolonged mixing may lead to undesirable shredding of fibres. There is no physico-chemical bond between fibre and the matrix, only a mechanical bond is formed as cement paste penetrates the mesh structure between individual fabrics of chopped length or continuous network.

10.1.2.1 Properties of fresh PFR concrete

- The compacting factor test has been reported to be most suitable. The inclusion of polypropylene fibres reduces the workability considerably, e.g., a normal concrete mix of medium workability (C.F. about 1.14) may reduce to a low workability mix (C.F. about 1.33) following the addition of 1% of chopped 35 mm polypropylene fibres. Polypropylene monofilaments can be used in small volume fractions of about 0.1 to 0.2% to alter rheological properties of the material, e.g., highly air-entrained concretes can be stabilised by fibres.

10.1.2.2 Properties of hardened PFR concrete

- The tensile strength of concrete is essentially unaltered by the presence of a small volume of short polypropylene fibres. Although the change in flexural strength of polypropylene reinforced-concrete is marginal; the post-cracking behaviour has shown its ability to continue to absorb energy as fibres-pullout. The energy absorbing capacity has been found to increase with the length of fibres, e.g. the 75 mm polypropylene fibres may result in an energy absorption comparable to that of the less efficient of steel fibres, and at a considerably lower cost.

10.1.2.3 Durability of PFR concrete

- Polypropylene may deteriorate under attack from ultra violet radiation or by thermal oxidation process. The cement matrix appears to prevent the former. To combat thermal oxidation, sophisticated stabilisers have been developed to delay degradation and enhance durability.

10.1.2.4 Applications of PFR mortar and concrete

- Cladding panels:
  Inclusion of polypropylene fibres instead of steel mesh reinforcement may allow reduction in panel thickness.
- *Shotcreting*:
  Surface coatings of polypropylene reinforced-mortar may be provided by shotcreting using normal equipment. The fibres of about 20 mm length enable smooth Transport of the dry mix through air hoses and nozzles. Water is then added at the gun orifice. Shotcreting can be advantageously used in wet environments where polypropylene fibres can eliminate the need for steel (corrodable) mesh on which spray of mortar is required.
- Polypropylene concrete:
  That type of concrete can be advantageously used in the energy dissipating blocks.

The potential market for polypropylene reinforced-cement is, principally, as a substitute for asbestos-cement roofing and cladding panels.

10.1.3 Glass-fibre Reinforced Concrete (GFR)

Glass fibres are made up from 200 to 400 individual filaments which are lightly bonded to make up a strand. These strands can be chopped into various lengths or combined to make cloth, mat or tape. Using the conventional mixing technique for normal concrete, it is not possible to mix more than about 2% (by volume) of fibres of up to a length of 25 mm.

The major application of glass fibre has been in reinforcing the cement or mortar matrices used in production of thin-sheet products. The commonly used varieties of glass-fibres are E-glass used in the reinforcement of plastics, and AR-glass. E-glass have inadequate resistance to alkalis present in Portland cements whereas AR-glass have improved alkali-resistant characteristics. Sometimes polymers are also added in the mixes to improve some physical properties such as moisture movement.

The process of manufacture of glass-fibre cement products may involve spraying, premixing or incorporation of continuous roving. In the spray-suction process, the glass-fibre strand is chopped into lengths between 10 to 50 mm and blown in spray simultaneously with the mortar slurry on to a mould or flat bed followed by suction to remove excess water. On the other hand in the technique involving premixing short strands (about 25 mm in length) are mixed into mortar paste or slurry before further processing by casting into open moulds, pumping into closed moulds, etc. Care must be taken to avoid fibre tangling and matting together, and to minimise the fibre damage during mixing.

In the process incorporating continuous roving, the rovings are impregnated with cement slurry by passing them through a cement bath before they are wound on to an appropriate mandrel. Additional slurry and chopped fibres on to the mandrel and compaction can be achieved by the application of roller pressure combined with suction.

10.1.3.1 Properties of hardened GFR concrete

The behaviour of glass-fibre cement sheets under tensile force is typified by multiple cracking of the matrix. Longer fibres improve the ultimate failure stress. In wet environments, significant reduction in strength takes place. The material may become brittle on ageing.

One of the most important improvements in the property achieved by glass fibre is the spectacular improvement in impact strength. With the addition of for example 5% glass fibres, an improvement in the impact strength of up to 1500% can be registered as compared to plain concrete. With a 2% fibre content (up to 25 mm in length), the flexural strength is almost doubled. The second important improvement is in the resistance to thermal shock. Ductility also improves with an increase in strength and modulus of rupture.

The flexural strength of water stored and weathered specimens reduces with time and nearly equals that of the matrix alone. The reduction in energy absorption is similar to that in flexural strength. The **long-term durability** of glass fibre-reinforced cement can be improved by the addition of 15% polymer to the mortar matrix. The increase in matrix cost is balanced by the use of cheaper E-glass fibres.

10.1.3.2 Applications of GFR concrete

The glass fibre-reinforced cement finds its use in formwork systems, ducting, roofing elements, sewer lining, swimming pools, fire-stop partitioning, tanks and drainage elements, etc. Sometimes it is used in combination with polymer impregnated in situ concrete.

10.1.4 Asbestos Fibres

The naturally available inexpensive mineral fibre, asbestos, has been successfully combined with Portland cement paste to form a widely used product called asbestos cement. Asbestos fibres have thermal, mechanical and chemical resistance making them suitable for sheet products, pipes, tiles and corrugated roofing elements. Asbestos-cement products contain about 8 to 16% (by volume) of asbestos-fibres. The flexural strength of asbestos cement board is approximately two to four times that of unreinforced matrix. However, due to relatively short length (10 mm), the fibres have low impact strength. There are health hazards associated with the use of asbestos cement. In the near future, it is likely that cellulose, PP, PVA or glass fibre-reinforce concrete will replace asbestos completely.

10.1.5 Carbon Fibres

Carbon-fibres form the most recent and probably the most spectacular addition to the range of fibres available for commercial use. Carbon fibres come under the high E-type fibres. These are expensive. Their strength and stiffness characteristics have been found to be superior even to those of steel. But they are more vulnerable to damage than even glass fibres, and hence are generally treated with resin coating.

10.1.6 Organic Fibres

Organic fibres, such as polypropylene or natural fibres may be chemically more inert than either steel or glass fibres. They are also cheaper, especially if natural. The polypropylene-fibre concrete has been described earlier. A large volume of vegetable fibres (7%, 50 mm length) may be used to obtain a multiple cracking composite. The problem of mixing and uniform dispersion may be solved by adding a superplasticizer.

10.1.7 Vegetable Fibres, and General Remarks

The commonly used fibres are jute, coir and bamboo. They possess good tensile strength in their natural dry state. Their tensile strengths do not suffer significantly even after being immersed in 10% solution of sodium hydroxide for up to 28 days. However, long-term durability is doubtful.

In contrast to glass fibres, steel, asbestos and polypropylene fibres are chemically stable in a cement paste matrix. The high alkalinity of cement paste protects steel from being corroded. The corrosion of steel fibres can however become a problem when the matrix has cracked.

Irrespective of the type, size and shape of fibres to be used in a mix, the fundamental requirement of fibre-reinforced concrete is that all the individual fibres should be uniformly distributed throughout the matrix. The mix should have sufficient paste content to coat the fibres and aggregate, so that the ingredients can be placed and compacted in the final position without any segregation.

The mix proportions generally depend on the intended applications of the composite. The prime considerations are uniform dispersion of fibres, adequate workability for placing and compaction with the available equipment. The workability of fibre-reinforced concrete is influenced by maximum size of aggregate, volume fraction, geometry and aspect ratio of fibres.

As the size of aggregate increases, it becomes more difficult to achieve uniform fibre dispersion, since the fibres are bunched into mortar fraction which can move freely past the aggregate during compaction.

To obtain a better dispersion the coarse aggregate content is kept lower than a normal mix and the maximum size of aggregate is preferably limited to 10 mm. The mortar matrix (consisting of particles less than 4 mm) should be around 70%, and aggregate/cement ratio as low as 3 : 1. A fine-to-coarse aggregate ratio of 1 : 1 is often a good starting point for a mix trial. Water/cement ratio between 0.4 and 0.6, cement-content of 250 to 450 kg/m^3 are recommended for providing adequate paste content to coat large surface of fibres. Beyond a certain optimum content of fibres the workability of the composite decreases rapidly.

11. OTHER SPECIAL CONCRETES

11.1 Heavy-weight Concrete

Concrete with high density is required for instance for ballasting, for precast concrete used for construction in water sound proofing, and above all for radiation-shields of reactors, laboratories, protective rooms, etc. As absorption of radiation depends upon the concrete mass, the walls can be thinner when the concrete is heavier. Bulk densities from 2750 up to 5000 kg/m^3 can be reached.

Heavy concrete, of course, has to be as compact as possible, but high densities can only be obtained by using heavy aggregates. They are selected according to the purpose of their application and, in the case of radiation shields, also on the kind of radiation. Natural as well as artificial aggregates can be used; slag cements and high-alumina cements are preferred in some cases.

The following table gives an overview of fields of application for heavy concrete (medicine, research, technique industry):

Aggregates for preparation of radiation stable concrete

Source of radiation	Type of radiation	Applicable types of aggregate
Radio nuclides	Gamma-rays	**Aggregates with high density:** Baryte, slag from heavy metals, Ilmenite, Ferro-silicon, Magnetite, Ferro-phosphorous, Hematite, granulated steel
X-ray apparatus	X-rays	**Aggregates with high atomic number:** Baryte, slag from heavy metals
Cyclotron	Electron-rays	**Aggregates with crystal water:** Ilmenite, Serpentine
	Gamma-rays	**Aggregates with high absorption capacity:** Colemanite, Boron-ferrite, Bor-calcite, Bor-carbide
	Neutrons	
Atom reactor	Gamma-rays Neutrons	
	Neutrons	

11.2 Heat Resistant or Refractory Concrete

Heat resistant or refractory concrete is usually meant by concrete consisting of a high-alumina cement and a special refractory aggregate. Properly chosen cement and aggregate will enable the concrete to withstand temperatures up to 18000 °C. Such concretes are also used for cement kiln linings.

11.3 White and Coloured Concrete

White and coloured concrete for architectural purposes can be produced with white cement, „warm-tone" cement or a cement to which a colouring material has been added. Similar effects can be obtained by adding a pigment when mixing the concrete (maximum 10%, mostly 3 to 5%, of cement weight). Usually mineral pigments will be used (iron oxides, chrome oxides, cobalt spinels) but carbon black is possible, too..

11.4 Sand-Lime Concrete (Lime siliceous blocks)

Sand-lime concrete - as the name indicates is made of sand and lime in an autoclave process.

During the hydrothermal curing under pressure in the autoclave, the quartz of the sand reacts with lime forming calcium silicate hydrate, quite similar to those formed by hydration of Portland cement. As lime contains more calcium than cement, a lower quantity of lime is sufficient to obtain a similar effect.

The calcium silicate hydrate is the strength bearing phase:

- **Hydrothermal reaction:**

$$Ca0 + SiO_2 + H_2O \rightarrow CaO \cdot SiO_2 \cdot H_2O$$

The raw materials are quartz sand (>60% $Si0_2$) and quick lime (> 80% active Ca0); quick lime can be substituted by lime hydrate. The sand can be used unground or partly or entirely ground. Grinding can be done separately or together with the lime. To regulate the activity of the lime, retarders such as gypsum are added. The amount of water required for a definite consistency depends mainly upon the specific surface of the quick lime. The mix is immediately moulded and compacted. After a so-called aging time, steam-curing is performed in autoclaves at a pressure of 12 to 16 bars during 2 to 6 hours. Sand and lime quality as well as compacting and curing are responsible for the strength of the final product.

Sand-lime is mostly used in the form of bricks as wall-forming materials replacing clay or concrete bricks. Large precast elements are fabricated too; in this case, more attention is paid to the composition and the preparation of the raw mix.

The bulk weight of sand-lime bricks is 1500 to 2100 kg/m^3 the compressive strength is from 15 up to 60 MPa

11.5 Polymers in Concrete

11.5.1 General

Polymers (plastics) possessing special properties, which differ from those of inorganic materials, are also used in concrete but only for special applications.

11.5.1.1 Advantages of polymers are:

- Good chemical resistance
- Easily malleable and workable
- Air and water tight
- Low density

The physical properties can be varied in a wide range by the composition and admixtures. Due to certain unfavourable characteristics, however, the application, especially in buildings, is restricted.

11.5.1.2 Drawbacks of polymers:

- High deformation under load (creep)
- Low heat resistance
- High price

Plastics as compared to cement of the same weight are about 100 times more expensive or 30 times more by volume.

In the following, the application as a binding material in concrete and mortar is treated. Whereas admixtures are used in quantities of a tenth per mil (0.1‰) up to a few percents of the cement weight, 5 to 30 % of the cement weight are added in this case, so that polymers form a significant part of the concrete matrix.

11.5.2 Polymer Cement Concrete (PCC)

Polymer Cement Concrete is manufactured by adding a monomer emulsion during the mixing of ordinary fresh concrete. The polymerisation of this monomer is initiated after mixing.

The monomer of a plastic material is the basic molecule which is in a liquid state. By polymerisation, some thousands of molecules are bonded together in a chain or network, thus forming a solid plastic-material.

- The main **advantages of PCC** are:
  - Improved workability
  - Improved impact strength
  - Improved flexural strength
  - Reduced shrinkage
    (as a result of a lower water/cement ratio)
  - Lower Young-modulus
  - Higher Deformation limit (up to five times)
  - Better toughness
  - Less danger of cracking
  - Better bond to old concrete (e.g. for repairs)
- The **disadvantages** are:
  - High material cost
    (about five times that of ordinary concrete)
  - Worse creep characteristics
  - Long-time performance not yet completely determined

11.5.3 Polymer-Impregnated Concrete (PIC)

Polymer Impregnated Concrete is formed by impregnating the air voids in a normally hardened concrete with a monomer, and subsequently polymerising by heating or exposure to radiation. The polymer content of PIC depends on the volume of air voids in the original concrete and lies between 3 and 7% by volume. The following characteristics are claimed to have been improved as compared to the original concrete.

- Improved properties of polymer-impregnated concrete:
  - Compressive strength increases: 3 to 4 times
  - Tensile strength increases: 4 times
  - Young's modulus increases: 2 times
  - Water permeability and water absorption becomes negligible
  - Higher resistance to frost/thaw cycles
  - Higher resistance to chemical attacks

12. MORTAR

12.1 Overview

12.1.1 Definition of mortar:

- Mortar is a mixture of:
  - Cementitious material
  - Fine aggregate (sand)
  - Water
  - Admixtures (sometimes),

12.1.2 Application of mortar

- The most important types of mortar are:
  - Masonry mortar
  - Plastering mortar for exterior of structure
  - Plastering mortar for interior of structure

12.2 Cementitious materials for mortar preparation

- Portland cement
- Portland blast-furnace slag cement
- Portland pozzolan cement
- Masonry cement
- Quicklime
- Hydraulic lime
- Hydrated lime
- Gypsum

The combination of different cementitious materials is very often used in mortar practice.

12.3 Aggregates for mortar preparation

Natural or crushed sand is used as aggregate in mortar. The maximum grain size of aggregate varies with the type of mortar; generally it lies between 1 to 4 mm. The aggregate surface should be free of injurious amounts of organic impurities and friable particles.

12.4 Admixtures

The following admixtures are used for mortar preparation:

- Water-reducers
- Plasticizers
- Grouting admixtures
- Bonding admixtures
- Colouring admixtures

Just as for concrete, there are specified requirements for the storage, measurement and mixing of mortars.

In the following table are summarised typical mortar mixes used in Switzerland

Mortar mixes and their properties (plastic consistency)

Type of mortar	Cementitious material, kg/m³		Sand (dry), kg/m³	Compressive strength, MPa	
	OPC	Hydraulic lime		at 7 days	at 28 days
Cement mortar	300 to 450	---	1500 to 1620	10 to 20	14 to 30
Combined lime-cement mortar	100 to 150	200 to 300	1440 to 1620	1.8 to 3.2	3.0 to 5.5
Hydraulic lime mortar	---	300 to 400	1490 to 1570	0.4 to 0.7	0.8 to 1.4

12.5 Packaged, Dry Combined Materials for Mortar (Dry Mortar)

As the name indicates, „Packaged, dry combined materials for mortar" are combinations of cementing materials and aggregates which require only mixing water to be ready for use. The packages - in sacks or bulk (for order of large quantities) - are generally available at a production plant or building material supply stores. Several types of mortars, especially for rendering, are on the market. The plastics are sometimes added to the cementitious materials to improve the bond strength between structure surface and rendering.

12.6 Ready-Mixed Mortar

Ready-mixed mortar is a product of the ready-mix concrete industry. The development was started in Europe around 1975 - to compensate for the loss of input in the ready-mix concrete business.

Ready-mixed mortar is a trowel-ready and immediately applicable wet mortar; it is produced in the ready-mix concrete plant and transported to the building site in trucks commonly used in ready-mix business.

Ready-mixed mortar is a cement mortar with chemical admixtures. The components are usually:

- Portland cement
- Sand (fraction 0 to 2 mm)
- Water
- Admixtures: air-entraining agent and retarder, sometimes a stabiliser is added; the admixtures have following functions:
  - **Air-entraining agent:** to obtain the necessary workability and trowel flow through introduction of 20 - 25 % of air bubbles into mortar mix
  - **Retarder:** to keep the mortar workable during approx. 30 to 40 hours (up to 2 working days)

The mortar is discharged on the job site into containers with known capacity (0.25, 0.33, 1.0 m^3) and keeps its workability during the 30 - 40 hours. After the ready-mixed mortar is used (as laying mortar for brick-work and block-work), the normal hydration begins.

In some countries (Germany, Belgium) the production of ready-mixed mortar represented about 8 - 15% of the total of all the ready-mix concrete companies.

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